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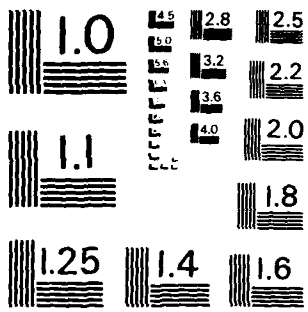

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AFGL-TR-82-0397
ENVIRONMENTAL RESEARCH PAPERS, NO. 817

Evaluation of Automated Imagery Analysis Algorithms for Use in the Three-Dimensional Nephanalysis Model at AFGWC

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28 December 1982

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This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-82-0397	2. GOVT ACCESSION NO. AD-A131986	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EVALUATION OF AUTOMATED IMAGERY ANALYSIS ALGORITHMS FOR USE IN THE THREE-DIMENSIONAL NEPHANALYSIS MODEL AT AFGWC		5. TYPE OF REPORT & PERIOD COVERED Scientific. Interim. 6. PERFORMING ORG. REPORT NUMBER ERP No. 817
7. AUTHOR(s) Robert P. d'Entremont, Rupert S. Hawkins, James T. Bunting		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Geophysics Laboratory (LYS) Hanscom AFB Massachusetts 01731		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62101F 66701701
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory (LYS) Hanscom AFB Massachusetts 01731		12. REPORT DATE 28 December 1982 13. NUMBER OF PAGES 39
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS (of this report) Unclassified 15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Satellite cloud analysis	Infrared imagery
Automated cloud analysis	Image processing
Cloud layer analysis	3D Nephanalysis

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Two different imagery analysis algorithms, one of which is currently in use by the 3DNEPH automated cloud analysis program at the Air Force Global Weather Central (AFGWC), and the other developed at AFGL, were evaluated and compared on a sample set of DMSP IR data (10.2 to 12.8 μm) with the aid of the AFGL Man-computer Interactive Data Access System. The 3DNEPH algorithm, MODAL, and the AFGL algorithm, CLUSTER, were designed to separate cloud layers in IR satellite imagery. Such information is used by the 3DNEPH to compute cloud analysis parameters as

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20. Abstract (continued)

percent cloud (earth) coverage and cloud heights. Both algorithms were found to perform well under some meteorological circumstances, but not so well under others. In general, however, it was found that CLUSTER performs better. The CLUSTER algorithm found clear/cloud boundaries, numbers of cloud layers, and fractional cloud covers that are closer to estimates made by analysts looking at corresponding IR and visible images. The MODAL algorithm found more cloud layers than were observed, and tended to overanalyze the transition regions between cloud layers.

Despite the overall advantages of CLUSTER, there is considerable room for improvement and algorithm development leading to improved cloud analysis. For instance, CLUSTER finds too many layers of cirrus clouds due to differing transparencies and sub-pixel sizes of cirrus cloud elements. It is possible to improve the cirrus layering problem by tuning the algorithm to be less sensitive to smaller thermal gradients at cold temperatures. CLUSTER can be tuned for other cloud types and levels as well.

The AFGWC has recognized the limitations of MODAL and the complications in its computer code. Subsequently, a substantially revised version of the 3DNEPH has been written, and is known as the Real-Time Nephanalysis (RTNEPH). With the continued cooperation of the AFGWC, we plan to evaluate this new program's image analysis algorithm and recommend changes and improvements for it, drawing on our experience with MODAL and CLUSTER.

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1. INTRODUCTION

An automated satellite cloud analysis system has been in use for over a decade at the Air Force Global Weather Central at Offutt AFB, Nebraska. This system is known as the 3DNEPH (Nephanalysis) Model and has been described by Coburn[1] and Fye.[2] It is a very comprehensive system that merges satellite imagery information and conventional meteorological data to produce global cloud analyses eight times a day. The infrared processor is an important component of this system, since the infrared image is the sole source of satellite information at night. Frequently this is the case during the day as well.

The major component of the infrared processor is an algorithm called MODAL that was designed to separate major regions or layers in a 25 x 25 n mi grid box which consists of an array of 8 x 8 infrared values having a nominal 3 n mi resolution. The MODAL algorithm is a histogram separation procedure that gives from one to four distinct regions or layers for each grid box. Our

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Received for publication 22 December 1982

1. Coburn, A. R. (1971) Improved Three-Dimensional Nephanalysis, AFGWC Technical Memorandum 71-2.

2. Fye, F. K. (1978) The AFGWC Automated Cloud Analysis Model, AFGWC Technical Memorandum 78-002.

objective is to try to understand this algorithm better. What are its weaknesses? Where are its strengths?

An algorithm developed by Hawkins[3,4] to analyze satellite data operates on infrared images, and can be configured to give much the same type of output as MODAL. This algorithm, called CLUSTER, separates the infrared images into mutually exclusive regions. All points are assigned to a region, whereas in MODAL some points may be left unassigned. In CLUSTER, as in MODAL, the number of regions can be from 1 to 4. We will alternately refer to these as layers or clusters. In MODAL analyses they have traditionally been called modes as well.

The object of this report is to describe MODAL and CLUSTER, and to compare the results of a large sample of cases where the two algorithms were run side by side. These evaluations are made possible by the AFGL Man-Computer Interactive Data Access System (McIDAS) which is an interactive computer system. The algorithms were programmed for the McIDAS, and a procedure was arrived at for comparing the two algorithms for different cloud situations. After some experimentation, a sample set of 350 cases was selected from smoothed (3 n mi) DMSP imagery. Each case consists of an array of 16 x 16 infrared grayshades, which means that each case contains 4 MODAL analyses, or a total of 1400 MODAL analyses for the entire study. The cases cover a wide range of cloud types, ground types, and combinations of cloud and ground. Considerable insight into the algorithms was gained by image analysts in reviewing these sets of data, and it is felt that the basic samples provide a well-rounded data set not only for this study but for further investigations.

2. DETAILS OF THE ALGORITHMS

The basic natures of the two algorithms studied here are very different since MODAL is a histogram evaluation algorithm and CLUSTER is a dynamic algorithm. Details of their structure and operation will now be given.

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3. Hawkins, Rupert S. (1980) A Clustering Technique for Satellite Image Analysis, Proc. 8th Conf. on Weather Forecasting and Analysis, Amer. Meteor. Soc., 115-118.

4. Hawkins, Rupert S. (1981) Objective Analysis of Satellite Cloud Imagery, Proc. 1981 International Geoscience and Remote Sensing Symposium, IEEE Geoscience and Remote Sensing Society, Volume 1, 477-482.

2.1 Introduction and Details of MODAL

The IR processor of the 3DNEPH merges infrared data, the surface and upper air temperature fields, and the geography and terrain fields to produce an eighth-mesh (25 n mi) cloud analysis on the 3DNEPH grid.[2] Cloud-top heights, temperatures, and total cloud amounts for up to two "most significant" layers are determined. ("Most significant" is defined in the 3DNEPH satellite processor as the two coldest layers separated by 1500 feet or more.)

The automated IR imagery analysis algorithm MODAL is the routine used by the 3DNEPH. MODAL is capable of detecting up to four layers, or modes, of clouds (including "clear" if it is present). It constructs a histogram of the IR grayshades (see Figure 1) of an 8 x 8 IR image array. These grayshades are

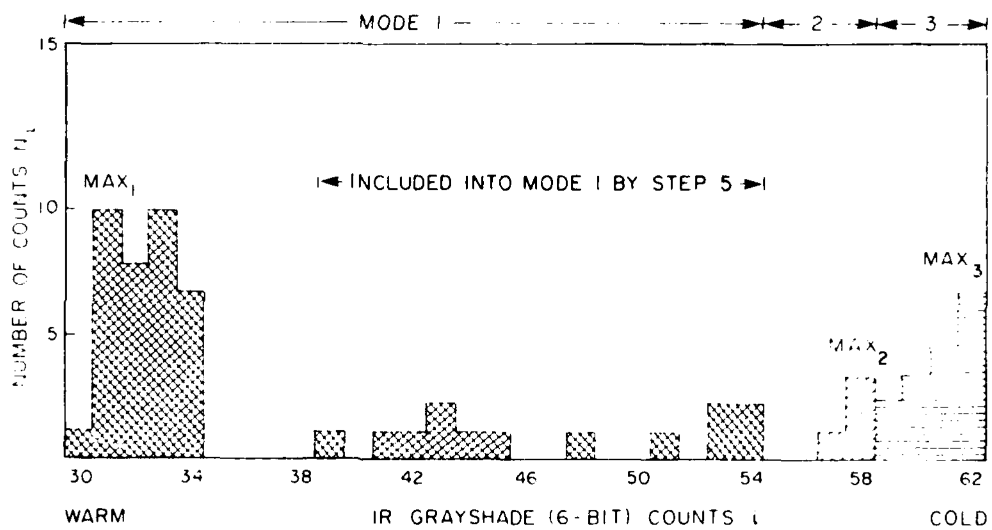

Figure 1. MODAL Histogram Analysis

then separated into modes (there are 3 modes in Figure 1) and a representative grayshade is determined. Using "COLD" as the coldest grayshade within a mode, "MEAN" as the average grayshade of a mode, and "MAX" as the most frequent grayshade within a mode, Table 1 lists the seven possible ways that a mode's representative grayshade is determined for the cloud/no-cloud decision, and for its height. Each mode's representative "height" grayshade value is first converted to an equivalent IR temperature, then corrected for water vapor

Table 1. Options for Representative Grayshades of a Mode

Scheme Number	Cloud/ No Cloud	Height
1.	COLD	COLD
2.	MAX	MAX
3.	MEAN	MEAN
4.	MAX	COLD
5.	MEAN	COLD
6.	MEAN	MAX
7.	MAX	MEAN

attenuation and look angle, and finally converted to the height of the mode using the eighth-mesh surface and upper air temperature profile. If the representative "cloud/no-cloud" temperature of a mode is not significantly different from the surface temperature, then that mode is flagged as "no cloud." The total cloud amount is determined by summing the number of pixels in the cloud mode(s) and dividing by the total number of pixels in the image array.

The choice of schemes in Table 1 allows for tuning of the 3DNEPH output to the needs of its users. Currently, the nephanalysis uses Scheme 1. Such a choice tends to overestimate the presence of clouds, since the cold point of a mode may be significantly colder than the MEAN or the MAX of the mode. This scheme also tends to overestimate the altitude of low clouds; however, this scheme may be best for semitransparent cirrus clouds since all of their grayshades may be warmer than the true cloud temperature. An example is given later. A description of the logic MODAL uses to distinguish cloud layers follows.

MODAL operates on the 6-bit IR image values of an 8 x 8-pixel array (25 n mi x 25 n mi nominal size). Its objective is to separate clear regions and cloud layers present in the image sample. The first function of the algorithm is to generate a histogram of the 8 x 8 array (see Figure 1). Modes are then defined in the following manner. All searching is done from the cold end of the histogram to the warm end, unless explicitly stated otherwise.

1. A search is made through the histogram for that grayshade that appears most frequently in the array. This grayshade is the mode of the mode, henceforth called MAX (see Figure 1). The number of grayshades of value MAX must

be ≥ 3. Let N_i = # of grayshades of value i. Thus, if $N_{MAX} < 3$, go to Step 5.

2. Grayshades that are one or two counts warmer or colder from MAX are then unconditionally assigned to the mode that MAX has begun to define; however, if any $N_{MAX \pm 1}$ or $N_{MAX \pm 2} = 0$ (a breakpoint), all further assignment of pixels to the mode on that side (warmer or colder) of MAX is terminated.

3. Further inclusion of any more grayshades i into this mode farther away than 2 grayshade values from MAX is strictly dependent on two conditions: (1) the number of pixels N_i must be greater than 0, and (2) the N_i must monotonically decrease with distance from MAX. As soon as either of these two conditions is not met, assignment of pixels to the mode of MAX is terminated. This is done on the warm and cold sides of MAX until either of the above conditions is broken or the end of the grayshade scale is reached, whichever comes first.

4. Go to Step 1, ignoring any pixels previously accounted for. Up to 4 modes are allowed. If 4 have been chosen, go to Step 5.

5. Go back and include any "leftover" pixels into existing modes if possible. Leftover pixels are those not accounted for in Steps 1-4. Leftovers are placed into the warmest mode that is closest to it (see Figure 1), and in no circumstance will leftover pixels warmer than the pixels in any mode be included in a mode. This ensures that clear pixels will not be inserted into cloudy modes; however, this also allows for some "unassigned" pixels.

There are some undesirable loopholes in this logic that are not immediately obvious. One situation exists when several pockets of IR grayshades with "peaks" (N_i's < 3) lie isolated from a mode so as not to be included in or assigned to that mode. In many cases, single breakpoints separate substantially large groups of pixels from what should perhaps be their own mode (see Figure 1). The 3DNEPH accounts for these pixels in total cloud calculations; however, subsequent layer calculations using the leftover pixels can unjustly increase cloud amounts and heights. Such is the case in Figure 1, Mode 1. The 24-grayshade spread of this mode, representing a ΔT of approximately 40° K, is much too great. Although the majority of the pixels in Mode 1 are concentrated around grayshade value 32, the 3DNEPH would choose as a representative value (using Scheme 1 of Table 1) the coldest grayshade in Mode 1, which is 54. The use of such a cold value for

this cloud layer seemingly must overestimate its height. It can potentially overestimate cloud presence as well for modes that have a mixture of clear and cloudy pixels.

Unassigned pixels appeared in 26.7 percent of the 1400 MODAL cases we studied. Most of the time the ΔT spread was considerably less than the 40°K in Figure 1 and many unassigned pixels were for cirriform clouds, for which a sizable ΔT is expected due to differing degrees of transparency of the cirrus clouds.

Another situation that commonly arises is that of overanalysis. On account of the monotonically decreasing criterion in Step 3, and the breakpoint criterion in Steps 2 and 3, MODAL tends to be too sensitive to small features in the image data. Figure 1 also demonstrates this point well. More logically, Modes 2 and 3 should be considered one mode. In general, MODAL identifies too many cloud modes and misses some clear areas. Some of this may be due, however, to the fact that satellite IR data is relatively more sensitive to high clouds than to low clouds. We have mentioned briefly a few of the apparent shortcomings of the MODAL analyses. We realize nonetheless that AFGWC is aware of these shortcomings and we anticipate that an updated IR image analysis algorithm in the RTNEPH will attempt to solve them. (The Real-Time NEPH [RTNEPH] is a substantial revision of the 3DNEPH scheduled for use in 1983.)

2.2 The CLUSTER Algorithm

CLUSTER was designed to analyze a 16 x 16 array of infrared imagery. Thus four 8 x 8 MODAL-type arrays are contained in one CLUSTER array and, in all the algorithm testing we have done, four MODAL arrays have been calculated for each CLUSTER array. The fact that CLUSTER runs on a 16 x 16 array does not restrict its potential application to the 3DNEPH since the critical grayshades determined by CLUSTER can be easily applied to the four 8 x 8 arrays within the 16 x 16 array to give separate estimates of cloud amounts and altitudes on the eighth-mesh or 25 n mi grid scale.

The first step of this algorithm is to separate the array into four quadrants. Histograms are obtained for sixteen intervals per quadrant. The action of the algorithm is to transform these histograms into clusters. At each step, transfers are made from quadrants having smaller frequencies in an interval to the quadrant having the largest frequency in that interval. This separates the data into unique clusters completely consistent with the overall frequency distribution of the whole area. The critical grayshades, which are the transition grayshades between clusters, are called cut levels.

The algorithm is essentially sequential, and can be stated, therefore, as a list of operations. Small loops sometimes occur within these steps, but no loop

occurs among or between steps. This characteristic makes for very fast execution as compared to algorithms that require many iterated calculations within large loops. The major steps in the clustering procedure follow:

STEP 1. Subscript the 16 x 16 infrared array by quadrants. This dimensioned variable could be labeled IR (4, 64). The four is for the four quadrants and the sixty-four for the 8 x 8 values within each quadrant.

STEP 2. The 3DNEPH grayshades (6-bit or 64 grayshades linear with temperature from 310 to 210°K) are placed in 16 intervals. The widths of the intervals are shown in Table 2, and are recognized to include all or nearly all meteorologically significant data. Interval 1 includes the warmest counts, and Interval 16 includes the coldest counts.

STEP 3. For each interval, place the sum of all four quadrant frequencies into the quadrant having the largest frequency value for that interval. If equals exist for "largest," leave for the next step. (Note that the quadrant data are now being transformed to cluster data.)

STEP 4. For those instances with two or more "largest" frequencies, place the sum at that interval into the quadrant having the largest sum in adjacent intervals.

STEP 5. If any quadrant (cluster) has less than thirteen points (5 percent of total coverage) place it in the nearest cluster.

STEP 6. For any cluster consisting of two parts (one or more zero intervals between non-zero frequencies), separate by putting one in a zero cluster if a zero cluster exists. If not, put the one closest to another cluster into that cluster.

STEP 7. Combine close clusters. This closeness value is one of the parameters open in the analysis. It was selected so that clusters consisting of values at only one interval and having a similar cluster one interval away in another cluster are combined into one cluster.

STEP 8. Eliminate clusters with less than 13 points (5 percent of coverage). This is used a second time since the separation of multiple clusters could create a small cluster.

STEP 9. Summarize cluster information; this includes the generation of histograms of clusters, number of clusters, and critical grayshades or cut levels that separate cloud regions from one another.

Table 2. Corresponding Interval Ranges for the 6-Bit DMSP Data Used in This Study. The temperature ranges are determined by linearly converting the ends of the corresponding grayshade intervals to °K

Interval	DMSP 6-Bit IR Grayshade Range	Temperature Range °K
16	52-63	227.3-210.0
15	49-51	232.2-229.0
14	47-48	235.4-233.8
13	44-46	240.1-237.0
12	42-43	243.3-241.7
11	39-41	248.1-244.9
10	37-38	251.2-249.7
9	34-36	256.0-252.8
8	32-33	259.2-257.6
7	29-31	264.0-260.8
6	27-28	267.1-265.6
5	24-26	271.9-268.7
4	22-23	275.1-273.5
3	19-21	279.8-276.7
2	17-18	283.0-281.4
1	0-16	310.0-284.6

These cut levels are the major result of the clustering routine. Along with the infrared values, they specify clustered regions that become the subject of interest, and represent a dimensional simplification of the imagery data. Figure 2 shows some results of calculations for a GOES IR image sample. Quadrant histograms appear on the left, and cluster histograms on the right. Summaries are given below these as marked.

3. SUMMARIES OF THE DATA SET

The data set used for this study was taken from nominal 3 n mi resolution Defense Meteorological Satellite Program Operational Linescan System (DMSP OLS) visible and IR data. Only IR data were actually processed, but corresponding visible images were used by the image analysts to help in making accurate subjective cloud amount and type classifications. The OLS is the primary sensor on DMSP spacecraft. It is a dual-channel scanning radiometer that senses reflected light and emitted infrared energy in the 0.4 to 1.0 μm and 10.2 to 12.8 μm spectral bands, respectively. A more advanced design of the OLS enables the earth sampling to vary much less in resolution as scanning proceeds from nadir to higher scan angles. The 3 n mi OLS data described in this report were smoothed twice: first,

GOES 8-BIT GRAYSHADE RANGE	INTERVAL #	UNCLUSTERED QUAD. FREQS.				CLUSTERED CLSTR. FREQS.			
206 - 255	16								
196 - 205	15								
186 - 195	14		3		17				20
176 - 185	13		8		38				46
166 - 175	12		3	3	3				9
156 - 165	11		2	1	3				6
146 - 155	10		1	3				4	
136 - 145	9		3	5	2			10	
126 - 135	8		1	4				5	
116 - 125	7	5	6	12	1			24	
106 - 115	6	6	9	9		24			
96 - 105	5	26	4	18		48			
86 - 95	4	22	6	8		36			
76 - 85	3	5	17	1			23		
66 - 75	2		1				1		
0 - 65	1								
	Σ 's	64	64	64	64	108	24	43	81

CLSTR. NO.	1	2	3	4
CUT LEVELS	85	115	155	
NO. OF PTS.	24	108	43	81
MEAN IR	79.6	98.9	128.6	179.9
MEAN VIS	40.2	53.0	64.0	71.7

Figure 2. Histogram Data Before and After Clustering With a Summary Below of the Four Clusters. This example is from an 8-bit IR GOES image

on the satellite from 0.3 n mi to 1.5 n mi, and then at AFGWC from 1.5 n mi to 3 n mi. Like the visible data, OLS IR data are digitized into one of 128 possible grayshade values on the satellite, and truncated to one of 64 possible values at GWC. The IR sensors are designed to detect a maximum equivalent blackbody temperature of 310°K and a minimum of 210°K. Warmer scenes, however, tend to have considerable atmospheric attenuation so that equivalent blackbody temperatures are less than true scene temperatures. Attenuation correction factors vary from 15° at 310°K down to 1° at 210°K.

The data set consists of 350 CLUSTER samples and their corresponding 1400 MODAL samples taken from a wide variety of atmospheric conditions ranging from clear to highly active cloud regions. While an effort was made to get as varied a sample as possible, the more prevalent cloud types occur more frequently within the set. Also, samples of land-water boundaries under clear skies were selected. The underlying consideration in making the data selection was to obtain as "complete" a sample as possible for testing algorithms such as MODAL and CLUSTER.

The samples are mostly from regions of feature transition. Flat regions were occasionally selected but, since these do not generally reveal much about the capabilities of the algorithms, samples that include more than one level or feature (that is, land/cloud) were ordinarily chosen. These levels range in contrast from multilayered cloud scenes to simpler clear/cloud scenes.

The data set was sent on tape by AFGWC to AFGL, and eighth-mesh samples were collected and saved using the McIDAS. Data and algorithm results were printed out for each of the 350 cases in the set. The results for Case 302 are shown in Figure 3. Data such as shown in Figure 3 was used to compare the performance of the algorithms. At the top of Figure 3 some information concerning which imagery the case came from is presented. The data, cloud types observed, and background (which were entered by the operator during the sample save generation) are given. The top array contains the original 6-bit infrared image values. (A value of 0 is warmest, and 63 is coldest.) Results of MODAL and CLUSTER are then listed in coded form. "L" represents the lowest layer (warmest mode or cluster), "." the next highest (next coldest) layer, "-" the next, and "H" the highest layer. (Note that if only two layers are found, "." represents the highest [coldest] one.) Grayshade ranges for the four MODAL arrays and one CLUSTER array are then given at the bottom of the printout.

Figure 3 also illustrates how the CLUSTER algorithm would easily generate a cloud analysis for 8 x 8 IR arrays (eighth mesh) or even 4 x 4 arrays (sixteenth-mesh). The critical grayshades or cut values can be determined for the 16 x 16 array, as CLUSTER already does. These cut values can then be applied to compute cloud parameters such as cloud cover estimates on 8 x 8 or 4 x 4 pixel subsets of the original 16 x 16 array.

The example in Figure 3 is for Sample 302 which, according to the operator's notes recorded at the time of the save, consists of about 50 percent cumulus buildups and 50 percent stratus buildups. Remember that MODAL's analyses are for four independently analyzed 8 x 8 arrays, all of which make up the 50 percent Cu and 50 percent St, and are merely positioned together in Figure 3 for comparison with the CLUSTER analysis. This causes some eventual irregularities in the layers' representative IR grayshades to occur from one 8 x 8 box to another, whereas a smooth analysis is generated by CLUSTER. Any such small-scale irregularities will be reflected in the cloud analysis output.

3.1 Categories of Clear and Cloudy Regions

The 350 cases were separated into seven basic categories. Table 5 shows the names of these categories along with the number of cases. From left to right

```
SAMPLE #302                MODAL-CLUSTER ANALYSIS   6-BIT IR GRAYSHADES

IMAGE 38002-130
ORBIT #2751          DEC. 17, 1979
TV LIN 312           CLOUDS: CR    ST
TV ELE 364           BKGND: WAT

         27 28 29 29 30 31 32 33 35 35 39 39 36 31 30 30
         29 29 28 32 31 32 34 34 36 39 41 40 35 30 30 30
         29 28 32 33 31 32 33 35 38 40 42 39 34 30 30 30
         32 29 34 35 32 32 34 35 38 41 43 39 34 30 30 30
         34 31 35 35 33 33 34 37 40 42 43 38 34 31 30 30
         33 32 35 35 33 35 36 38 40 41 41 37 35 31 30 29
         36 37 39 35 33 35 38 39 42 42 39 34 34 31 30 30
         38 40 39 34 34 35 37 39 43 42 40 36 32 30 30 29
         38 40 38 35 33 35 37 40 42 42 39 39 34 30 30 30
         38 40 39 34 35 37 38 42 43 39 38 39 33 30 30 30
         40 40 38 34 34 36 39 43 43 40 37 38 33 30 30 30
         42 41 39 34 34 36 39 43 43 39 38 38 34 30 30 29
         42 42 37 33 34 38 41 44 42 36 37 38 31 29 30 29
         42 41 35 32 34 38 42 44 41 37 38 39 33 29 29 29
         42 39 32 33 37 40 43 44 40 37 40 41 34 29 29 29
         41 36 32 33 37 40 44 43 37 36 38 40 33 29 29 29

      MODAL ANALYSIS                               CLUSTER ANALYSIS
L L L L . . . - . . - - . L L L           L L L L L L . . . . - - . L L L
L L L . . . - - . - - - . L L L           L L L . L . . . . - - - . L L L
L   . - . . - - - - H - . L L L           L L . . L . . . - - H - . L L L
. L - - . . - - - - H - . L L L           . L . . . . . . - - H - . L L L
- . - - - - - - - H H - . L L L           . L . . . . . - - H H - . L L L
- . - - - - - - - - - - . L L L           . . . . . . . - - - - - . . L .
- - H - - - - H H H - . . L L L           . - - . . . - - H H - . . L L L
- H H - - - - H H H - . L L L L           - - - . . . - - H H - . . L L L
. . . L L L . . H H - - . L L .           - - - . . . - - H H - - . L L L
. . . L L . . - H - - - . L L L           - - - . . - - H H - - - . L L L
. . . L L . . - H - - - . L L L           - - - . . . - H H - - - . L L L
- . . L L . . - H - - - . L L L           H - - . . . - H H - - - . L L L
- - . L L . . - H - - - L L L L           H H - . . - - H H . - - L L L L
- . L L L . - - - - - - . L L L           H - . . . - H H - - - - . L L L
- . L L . . - - - - - - . L L L           H - . . - - H H - - - - . L L L
. . L L . . - - - - - - . L L L           - . . . - - H H - . - - . L L L
```

	# MODES	MODE 1=L RNG	CNTS	MODE 2=. RNG	CNTS	MODE 3=- RNG	CNTS	MODE 4=H RNG	CNTS	#	CLUSTER RNG	CNTS	%
QUADRANT 1	4	27-29	9	30-32	14	33-38	35	39-40	5	1=L	0-31	64	25
QUADRANT 2	4	29-32	25	34-36	12	37-41	19	42-43	8	2=.	32-36	81	31
QUADRANT 3	3	32-35	18	36-41	31	42-44	15	0- 0	0	3=-	37-41	82	32
QUADRANT 4	4	29-31	25	33-34	7	36-41	26	42-43	6	4=H	42-63	29	11

Figure 3. MODAL and CLUSTER Analysis for Case 302

these are Clear Land/Water/Snow, Cumulus, Stratus, Stratocumulus, Cirrostratus, Cirrus, and Cumulonimbus.

Table 3. Composition of the Cloud Imagery Sample Set

CLL/CLW/CLS	Cu	St	Sc	Cs	Ci	Cb
48	85	45	39	16	92	25

This separation is done on the basis of the major classification (the most dominant type) for each sample. Minor constituents usually occur in all cases except clear land or clear water. We feel that this sample is more than adequate for evaluating MODAL and CLUSTER-type algorithms. The fundamental drawback in the evaluation of such algorithms is the subjective approach that is required to settle on (a) what is desired of an algorithm like MODAL, and (b) once decided upon, how well MODAL and other algorithms meet those criteria. The criteria we feel to be of importance are enumerated in the following paragraphs. Also stated is the rationale for separating a grid box into regions or layers.

Separation of basic features for making simple accurate statements about grid boxes is the goal. In the 3DNEPH these features (regions) are referred to as layers. Naturally, layers standing out from other layers are most desired to be separated. Two layers hardly distinguishable from each other should be analyzed as one layer. Both the size of the area and how much the area stands out from adjacent areas should determine whether or not it qualifies as an independent layer. These goals are not stated explicitly; however, they are implicitly included in algorithms that perform the separation.

The separation should be mutually exclusive. In other words, the sum of all the layers/clusters should constitute the whole grid box area. Among other things, this makes for a complete analysis and more meaningful data reduction than if this is not a requirement. CLUSTER has this feature. MODAL lacks this feature since sometimes IR values are not assigned to modes; however, subsequent processing in the 3DNEPH decides whether the unassigned IR values are clear or cloudy.

The sensitivity of the separating algorithm should be reasonable from the warmest equatorial regions to the coldest polar regions. It would also be an

advantage if it could be tuned to give a desired response. Both MODAL and CLUSTER are open to tuning, but CLUSTER is far more flexible in this respect.

For operation in the 3DNEPH model, fast computer times are required to perform the analysis due to real-time processing constraints. If an algorithm is not fast enough it cannot qualify for use by the 3DNEPH. Of course, MODAL satisfies these requirements. Our experiments with run times show that, on an average, MODAL takes 0.026 seconds, and CLUSTER takes 0.094 seconds. Comparing area-weighted times, CLUSTER runs a little faster than MODAL does.

3.2 Evaluation of the Two Algorithms in Terms of the Seven Basic Categories

Clear. From the point of view of region separation, this is a simple category. Problems arise not from algorithm inadequacies, but from the very nature of the IR data. There are instances when low clouds blend into the surface temperatures and, consequently, are not separated by either MODAL or CLUSTER. Therefore, clear regions and scattered cumulus conditions are often difficult to separate satisfactorily. Figure 4 illustrates how the 16 x 16 CLUSTER array size has a "context" advantage over MODAL, when scattered cumulus are present in an otherwise clear area. CLUSTER identifies two distinct layers, compared to just one layer for MODAL.

In warmer regions where land temperatures approach those of water, subtle land/water distinctions are barely discernible by the IR sensor, and commonly indiscernible by the MODAL and CLUSTER algorithms (Figures 5 and 6). Wherever temperature contrasts are great enough, neither MODAL nor CLUSTER has serious problems in land/water separations.

Cumulus. There are several problems with the ability of both MODAL and CLUSTER in the analysis of Cu. Most of these problems, however, are due to the physical nature of the clouds themselves. They generally do not fill the field of view of the sensor. Thus, calculations of total cloud are difficult to perform, especially on a pixel-by-pixel basis as the 3DNEPH essentially operates. An IR pixel that represents a Cu cloud that partially fills that pixel contaminates the grayshade: the temperature that grayshade represents is actually representative of some cloud and some ground radiation. The observed temperature is warmer than the actual cloud element's temperature, but colder than the underlying surface temperature. When the algorithms compare such a temperature to an adjacent clear pixel, the difference in temperature (grayshade) may or may not be enough to allow MODAL or CLUSTER to distinguish between a partially cloud-filled region and a clear region. It should be noted that this is not necessarily an algorithm problem, but a physical one due to IR sensor characteristics, field

```
SAMPLE #157          MODAL-CLUSTER ANALYSIS   6-BIT IR GRAYSHADES

IMAGE 24002-120
ORBIT #2479          DEC. 25, 1979
TV LIN 555           CLOUDS: CU   CL
TV ELE 315           BKGND: LAN

      21 20 21 21 21 21 20 20 20 21 21 20 20 20 20 20
      21 20 21 21 21 21 21 21 21 21 20 20 20 20 20 20
      21 21 21 21 21 21 21 21 21 21 20 20 20 20 20 21
      21 21 21 21 21 21 21 21 21 21 20 20 20 20 23 24
      20 21 21 21 20 20 20 20 21 20 20 21 21 21 21 21
      20 20 20 20 20 20 20 20 20 20 20 21 20 20 21 21
      20 20 20 20 20 20 20 20 20 20 21 20 20 20 20 19
      20 20 20 18 18 19 19 20 20 20 20 20 20 19 19 17
      19 17 15 14 14 14 15 15 14 14 15 15 16 14 14 15
      13 14 13 13 14 14 15 15 14 14 15 16 15 16 15 14
      14 14 14 13 13 13 13 14 14 14 14 15 15 16 15 15
      15 14 13 13 12 12 13 13 14 14 13 13 14 13 13 13
      15 14 13 12 13 12 13 13 13 14 14 13 12 13 13 13
      13 14 14 13 13 14 14 13 13 14 14 13 13 13 13 14
      13 14 13 13 13 13 13 13 14 14 14 17 18 17 15 15
      13 13 13 13 12 12 13 13 15 17 18 16 15 16 15 16

     MODAL ANALYSIS                       CLUSTER ANALYSIS
L L L L L L L L L L L L L L L L      . . . . . . . . . . . . . . . .
L L L L L L L L L L L L L L L L      . . . . . . . . . . . . . . . .
L L L L L L L L L L L L L L L L      . . . . . . . . . . . . . . . .
L L L L L L L L L L L L L L L L      . . . . . . . . . . . . . . . .
L L L L L L L L L L L L L L L L      . . . . . . . . . . . . . . . .
L L L L L L L L L L L L L L L L      . . . . . . . . . . . . . . . .
L L L L L L L L L L L L L L L L      . . . . . . . . . . . . . . . .
L L L L L L L L L L L L L L L L      . . . L L . . . . . . . . . L L
L L L L L L L L L L L L L L L L      . L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L      L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L      L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L      L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L      L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L      L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L      L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L      L L L L L L L L L L L L L L L L

               #    MODE 1=L   MODE 2=.   MODE 3=-   MODE 4=H        CLUSTER
             MODES  RNG CNTS   RNG CNTS   RNG CNTS   RNG CNTS   #    RNG CNTS  %
QUADRANT 1     1    18-21 64    0- 0  0    0- 0  0    0- 0  0  1=L   0-18131   51
QUADRANT 2     1    17-24 64    0- 0  0    0- 0  0    0- 0  0  2=.  19-63125   48
QUADRANT 3     1    12-19 64    0- 0  0    0- 0  0    0- 0  0  3=-   0- 0  0
QUADRANT 4     1    12-15 64    0- 0  0    0- 0  0    0- 0  0  4=H   0- 0  0    0
```

Figure 4. MODAL and CLUSTER Analysis for Case 167

```
SAMPLE #348            MODAL-CLUSTER ANALYSIS   6-BIT IR GRAYSHADES

IMAGE 30002-120
ORBIT #2737          DEC. 16, 1979
TV LIN 373           CLOUDS: CLL  CLW
TV ELE 208           BKGND: MIX

      12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12
      12 12 13 12 12 12 12 12 12 12 12 12 12 12 12 12
      12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12
      12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12
      12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12
      12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12
      12 12 12 12 12 12 12 12 12 12 12 12 12 11 11 11
      12 12 12 12 12 12 12 12 12 12 11 11 11 11 11 11
      12 12 12 12 12 11 11 11 11 10 10 11 11 11 11 11
      11 11 11 11 11 10 11 11 11 11 11 11 10 10 11 11
      10 11 11 11 11 11 11 11 11 10 10 11 11 11 11 11
      11 10 10 10 11 11 11 11 11 10 11 10 11 11 11 11
      11 11 10 10 10 10 10 11 11 11 10 10 11 11 11 11
      11 10 10 10 10 10 11 11 11 11 11 11 11 11 11 11
      10 10 10 10 11 11 11 10 11 11 11 11 11 11 11 11
      11 11 11 11 11 11 11 10 10 11 11 11 11 11 11 11

    MODAL ANALYSIS                              CLUSTER ANALYSIS
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L           L L L L L L L L L L L L L L L L
```

	# MODES	MODE 1=L RNG	CNTS	MODE 2=. RNG	CNTS	MODE 3=- RNG	CNTS	MODE 4=H RNG	CNTS	#	CLUSTER RNG	CNTS	%
QUADRANT 1	1	12-13	64	0- 0	0	0- 0	0	0- 0	0	1=L	0-63	256	100
QUADRANT 2	1	11-12	64	0- 0	0	0- 0	0	0- 0	0	2=.	0- 0	0	0
QUADRANT 3	1	10-12	64	0- 0	0	0- 0	0	0- 0	0	3=-	0- 0	0	0
QUADRANT 4	1	10-11	64	0- 0	0	0- 0	0	0- 0	0	4=H	0- 0	0	0

Figure 5. MODAL and CLUSTER Analysis for Case 348

```
SAMPLE # 60            MODAL-CLUSTER ANALYSIS   6-BIT IR GRAYSHADES

IMAGE 35002-130
ORBIT #2690          DEC. 12, 1979
TV LIN 361           CLOUDS: CLL  CLM
TV ELE 185           BKGND: MIX

        12 12 13 13 13 12 12 12 12 12 12 12 12 12 12 12
        12 12 13 13 13 13 12 12 12 12 12 12 12 12 12 13
        12 12 12 13 12 13 13 12 12 12 12 12 12 12 13 12
        12 12 12 12 12 12 12 12 12 12 12 12 12 13 13 12
        12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12
        14 13 12 12 12 13 13 13 13 12 12 12 13 13 13 12
        15 15 14 13 12 12 12 12 13 14 14 15 14 13 12 12
        15 15 15 15 14 13 12 12 12 13 14 15 15 14 12 12
        15 15 15 15 15 14 13 13 13 12 13 15 15 15 13 12
        15 15 15 15 15 15 15 15 14 14 14 15 15 15 13 12
        15 15 15 15 15 15 15 15 14 15 15 15 15 15 13 12
        15 15 15 15 15 15 15 15 15 14 15 14 13 13 14 13
        15 15 15 15 15 15 15 15 15 15 14 14 14 13 12 13
        15 15 15 15 15 15 15 15 15 15 15 15 15 15 13 13
        15 15 15 15 15 15 15 15 15 15 15 15 14 15 15 13
        15 15 15 15 15 15 15 15 15 15 15 15 15 14 14 14

       MODAL ANALYSIS                          CLUSTER ANALYSIS
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
. . L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
. . . . L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L

                #   MODE 1=L  MODE 2=.  MODE 3=-  MODE 4=H        CLUSTER
              MODES RNG CNTS  RNG CNTS  RNG CNTS  RNG CNTS   #    RNG CNTS  %
QUADRANT 1     2    12-14 58  15-15  6   0- 0  0   0- 0  0  1=L  0-63256 100
QUADRANT 2     1    12-15 64   0- 0  0   0- 0  0   0- 0  0  2=.  0- 0   0   0
QUADRANT 3     1    13-15 64   0- 0  0   0- 0  0   0- 0  0  3=-  0- 0   0   0
QUADRANT 4     1    12-15 64   0- 0  0   0- 0  0   0- 0  0  4=H  0- 0   0   0
```

Figure 6. MODAL and CLUSTER Analysis for Case 60

of view, and atmospheric attenuation. Nonetheless, CLUSTER seems to handle these situations more favorably than MODAL, since MODAL "tries too hard" to separate subtle changes in grayshade. Separation of Cu from higher layers does not present a problem for either algorithm.

Figures 7 and 8 illustrate the action of the two algorithms on cumulus fields. First, notice that MODAL overanalyzes (provides seemingly irrelevant detail) in some places, and that CLUSTER gives an apparently neater analysis. Points not analyzed into a level by MODAL are blank in the illustrations. These points are warmer than the warmest mode (see Step 5 of MODAL in Section 2.1). While the two cases represent specific situations that are not that frequent in the data samples, they do indicate MODAL's apparent problem of overanalyzing the image data. MODAL might be characterized as being "oversensitive" to small changes over small distances. Some of the variability in the MODAL analysis occurs at the boundaries of the quadrants. MODAL is not at fault here since the individual quadrants may have appropriate layers. It must be remembered that the MODAL mapping is made up of four independent runs. Symbols may not represent the same temperature range from one quadrant to the next.

Stratus. Neither MODAL nor CLUSTER has a problem with flat fields of data. Stratus is one cloud type on which the two algorithms behave similarly. There are cases to be found throughout the stratus samples that support this observation; however, again there is a tendency for MODAL to be oversensitive, and put in more layers than necessary.

Stratocumulus. Stratocumulus poses less of a problem than cumulus since these clouds tend to fill more of the field of view. Thus, many of the physical constraints inherent in cumulus detection and analysis are not so prevalent for the proper detection and analysis of Sc. Both MODAL and CLUSTER tend to find too many layers of Sc. They do not always do so on the same cases. Examples of MODAL overanalysis of Sc are in Figures 9, 10, and 11, and for CLUSTER in Figures 12, 13, and 14. Both are finding subtle changes in the temperatures of cloud fields. We feel that the cloud analysis would be improved if this sensitivity was tuned out of the algorithm to be used in the 3DNEPH.

Cirrostratus. Cirrostratus fields tend to appear flat and are generally well-analyzed, since temperature differences among these ice clouds and most any other categories in an image are great. While both algorithms perform well, MODAL has the tendency to find too many layers, as noted in other categories (see Figure 15, for example).

```
SAMPLE #312            MODAL-CLUSTER ANALYSIS   6-BIT IR GRAYSHADES

IMAGE 20002-110
ORBIT #2737            DEC. 16, 1979
TV LIN 314             CLOUDS: CU   CLL
TV ELE 330             BAGND: LAN
```

18	15	14	14	14	15	17	27	35	40	43	48	49	41	40	24
14	14	15	15	14	15	18	27	35	45	43	46	50	53	52	36
13	15	15	14	16	16	18	24	35	45	47	48	52	54	54	52
13	13	14	14	15	17	17	21	32	46	50	50	50	53	53	49
13	13	13	14	15	16	17	21	30	40	49	52	55	56	55	52
13	13	13	13	15	15	17	19	25	38	49	53	56	56	56	56
13	13	13	13	14	15	16	19	23	31	41	48	54	55	54	53
14	14	14	13	15	15	15	15	17	23	30	40	43	43	47	52
14	15	14	13	13	14	14	15	16	19	24	29	36	42	46	45
13	13	13	14	14	13	13	14	15	16	18	25	26	29	29	39
13	13	13	13	13	13	14	14	14	15	16	20	23	29	34	37
13	13	13	13	13	13	13	14	14	14	15	16	22	26	27	24
13	13	13	13	13	13	13	14	14	15	15	15	17	20	21	20
13	14	14	14	14	14	14	14	15	15	15	16	16	19	22	26
13	14	14	14	15	15	16	15	17	16	16	19	21	23	23	21
14	14	15	15	15	14	15	15	16	18	22	22	21	22	22	20

```
        MODAL ANALYSIS                           CLUSTER ANALYSIS
L L L L L L L L   L . .                  L L L L L L L - - - - - - - - .
L L L L L L L L   L L . . - -            L L L L L L L - - - - - - - - -
L L L L L L L L   . . . - - - -          L L L L L L L . - - - - - - - -
L L L L L L L L   . . . . - - .          L L L L L L L . - - - - - - - -
L L L L L L L L     . - - H - -          L L L L L L L . - - - - - - - -
L L L L L L L L     . - H H H H          L L L L L L L . . - - - - - - -
L L L L L L L L       . - - - -          L L L L L L L . . - - - - - - -
L L L L L L L L         L L . -          L L L L L L L L L . - - - - - -
L L L L L L L L L . . H H H H H          L L L L L L L L L . . - - - - -
L L L L L L L L L L L . - H H H          L L L L L L L L L L L . . - - -
L L L L L L L L L L L . . H H H          L L L L L L L L L L L . . - - -
L L L L L L L L L L L L . - - .          L L L L L L L L L L L L . . - .
L L L L L L L L L L L L L . . .          L L L L L L L L L L L L L . . .
L L L L L L L L L L L L L . . -          L L L L L L L L L L L L L . . .
L L L L L L L L L L L . . . . .          L L L L L L L L L L L . . . . .
L L L L L L L L L L . . . . . .          L L L L L L L L L L . . . . . .
```

	# MODES	MODE 1=L RNG CNTS	MODE 2=. RNG CNTS	MODE 3=- RNG CNTS	MODE 4=H RNG CNTS	#	CLUSTER RNG CNTS	%
QUADRANT 1	1	13-27 64	0- 0 0	0- 0 0	0- 0 0	1=L	0-18 149	57
QUADRANT 2	4	43-43 5	45-50 15	52-55 18	56-56 5	2=.	19-26 35	13
QUADRANT 3	1	13-15 64	0- 0 0	0- 0 0	0- 0 0	3=-	27-63 73	28
QUADRANT 4	4	14-17 26	19-25 23	26-27 4	29-46 11	4=H	0- 0 0	0

Figure 7. MODAL and CLUSTER Analysis for Case 312

```
SAMPLE #342            MODAL-CLUSTER ANALYSIS   6-BIT IR GRAYSHADES

IMAGE 30032-120
ORBIT #2737            DEC. 16, 1979
TV LIN 257             CLOUDS: CU   ST   CLR
TV ELE 215             BKGND: WAT

        20 18 21 25 30 32 33 32 32 32 32 32 32 36 39 39
        19 19 27 31 32 32 32 32 32 33 33 33 34 35 34 34
        24 25 24 31 33 32 31 31 31 32 34 37 37 35 34 33
        26 32 32 33 33 32 30 31 30 31 34 36 37 36 36 35
        29 32 33 33 34 33 31 29 30 31 33 35 33 33 35 36
        26 29 32 34 34 33 23 19 23 26 29 31 29 35 38 38
        24 25 30 33 33 31 21 23 27 25 26 29 30 35 38 39
        27 28 31 33 34 32 27 28 28 26 24 26 31 35 38 42
        31 30 31 35 37 34 33 30 29 27 25 30 36 39 42 43
        32 33 34 35 36 34 32 28 37 36 32 36 42 44 51 51
        35 35 37 36 37 37 34 30 36 39 44 48 51 54 56 55
        35 37 42 39 38 37 41 43 45 55 57 56 54 56 57 54
        [illegible] 45 45 50 48 42 45 52 55 55 55 54 54 53 51 51
        58 58 58 56 53 52 55 55 53 53 52 50 49 49 47 48
        59 55 54 53 54 52 54 52 48 47 50 50 48 48 45 44
        55 55 53 52 50 51 45 47 45 44 44 48 51 49 50 50

       MODAL ANALYSIS                          CLUSTER ANALYSIS
L L L . - - - - . . . . . . - -        L L L L L L L L L L L L L L . .
L L . - - - - - . . . . . . . .        L L L L L L L L L L L L L L L L
. . . - - - - - . . . . . . . .        L L L L L L L L L L L L L L L L
. - - - - - - - . . . . . . . .        L L L L L L L L L L L L L L L L
- - - - - - - - . . . . . . . .        L L L L L L L L L L L L L L L L
. - - - - - L L L L . . . . - -        L L L L L L L L L L L L L L L L
. . - - - - L L . L L . . . - -        L L L L L L L L L L L L L L L L
. . - - - - . . . L L L . . - -        L L L L L L L L L L L L L L L .
L   L . . L L               L L        L L L L L L L L L L L L L . . .
L L L . . L L           L L - -        L L L L L L L L L L L L . . . .
. . . . . . L       L . - H H H        L L L L L L L L L . . . . . . .
. . . . . . . . L - H H H H H H        L L . . L L . . . . . . . . . .
. . . - . . . - H H H H H - - -        . . . . . . . . . . . . . . . .
H H H - - - - - - - - - - - . .        . . . . . . . . . . . . . . . .
H - - - - - - - . . - - . . . L        . . . . . . . . . . . . . . . .
- - - - - - . . L L L . - - - -        . . . . . . . . . . . . . . . .
```

	# MODES	MODE 1=L RNG	CNTS	MODE 2=. RNG	CNTS	MODE 3=- RNG	CNTS	MODE 4=H RNG	CNTS	#	CLUSTER RNG	CNTS	%
QUADRANT 1	3	18-23	9	24-25	13	29-34	42	0- 0	0	1=L	0-38	163	63
QUADRANT 2	3	23-26	7	27-37	49	38-42	9	0- 0	0	2=.	39-63	[illegible]	36
QUADRANT 3	4	31-34	10	35-49	25	50-56	20	58-59	4	3=-	0- 0	0	0
QUADRANT 4	4	42-45	10	46-48	9	49-53	19	54-57	14	4=H	0- 0	0	0

Figure 8. MODAL and CLUSTER Analysis for Case 342

```
SAMPLE # 15              MODAL-CLUSTER ANALYSIS   6-BIT IR GRAYSHADES

IMAGE 36002-130
ORBIT #2623          DEC. 8, 1979
TV LIN 131           CLOUDS: SC
TV ELE 283           BKGND: WAT

      25 27 28 28 29 29 29 29 24 23 21 22 23 23 21 24
      30 30 30 31 31 30 29 29 27 24 23 21 24 24 21 28
      31 31 31 31 30 27 30 29 26 21 22 21 27 29 22 24
      31 31 31 31 30 30 30 28 24 21 23 24 26 22 21 23
      31 30 31 31 30 28 25 22 21 22 21 20 20 21 24 26
      31 31 31 30 28 23 22 23 21 20 20 20 21 26 30 28
      31 30 30 26 27 28 27 27 23 21 20 20 24 29 30 30
      29 25 27 29 29 29 27 26 23 20 20 20 26 30 29 28
      28 29 27 27 29 29 30 25 21 20 20 20 23 24 25 26
      29 30 30 30 30 30 30 28 24 20 22 23 24 26 27 29
      30 30 30 29 29 30 30 28 21 21 24 27 30 30 29 30
      31 29 29 28 28 29 27 22 19 23 24 28 29 30 27 24
      30 30 30 26 26 26 22 20 21 27 27 29 28 28 27 28
      30 29 27 27 23 26 22 20 24 27 28 27 27 25 25 27
      22 25 29 26 21 23 21 21 26 29 28 25 26 26 26 30
      21 27 29 24 23 22 20 21 26 26 24 24 28 25 29 29

        MODAL ANALYSIS                          CLUSTER ANALYSIS
L L L L _ L L _ . L L L L L L .         . . . . - - - - . L L L L L L .
L L L L L L L _ - . L L . . L -         - - - - - - - - . . L L . . . .
L L L L _ L L _ - _ L L - - L .         - - - - - . - - . L L L . - L .
L L L L _ L L _ . L L . - L L L         - - - - - - - . . L L . . L L L
L L L L _ L L   L L L L L L . -         - - - - - . . L L L L L L L . .
L L L L _       L _ L L L - H -         - - - - . L L L L L L L L . - .
L L L L _ L L . L L L L . - H H         - - - . . . . . L L L L . - - -
L L L L _ L L _ L L L L - H - -         . . . - - - . . L L L L . - - .
. . . . . . . . L L L L . . - -         . . . . - - - . L L L L L . . .
. . . . . . . . . L . . . - - -         - - - - - - - . . L L L . . . -
. . . . . . . . L L . - - - - -         - - - - - - - . L L . . - - - -
. . . . . . . _ L . . - - - - .         - - - . . - . L L L . . - - . .
. . . . . . L _ L - - - - - - -         - - - . . . L L L . . - . . . .
. . . . - . L _ . - - - - - - -         - . . . L . L L . . . . . . . .
L . . . - L L _ - - - - - - - -         L . - . L L L L . - . . . . . -
L . . . - L L _ - - . . - - - -         L . - . L L L L . . . . . . - -

              #    MODE 1=L  MODE 2=.  MODE 3=-  MODE 4=H       CLUSTER
            MODES  RNG CNTS  RNG CNTS  RNG CNTS  RNG CNTS   #    RNG CNTS  %
QUADRANT 1    1    25-31 60   0- 0  0   0- 0  0   0- 0  0  1=L   0-23 70  27
QUADRANT 2    4    20-23 37  24-24 10  26-29 13  30-30  4  2=.  24-28 99  38
QUADRANT 3    2    20-23 16  24-31 49   0- 0  0   0- 0  0  3=-  29-63 87  33
QUADRANT 4    3    19-21  9  22-24 13  25-30 42   0- 0  0  4=H   0- 0  0   0
```

Figure 9. MODAL and CLUSTER Analysis for Case 15

```
SAMPLE # 16          MODAL-CLUSTER ANALYSIS   6-BIT IR GRAYSHADES

IMAGE 36002-130
ORBIT #2623          DEC.  8, 1979
TV LIN 132           CLOUDS: SC
TV ELE 359           BKGND: WAT

      25 25 25 29 29 29 29 29 29 29 30 30 29 28 29 28
      19 21 28 29 29 30 29 29 29 29 29 29 28 29 25 19
      17 19 27 29 29 29 29 29 29 29 29 28 27 27 20 18
      22 28 29 28 29 29 29 29 28 28 28 26 22 17 16 16
      29 29 29 29 29 29 29 29 28 26 19 19 17 16 15 16
      29 29 28 28 28 29 28 24 18 15 15 17 17 17 19 22
      28 28 28 28 28 27 22 16 15 15 17 18 17 19 19 24
      28 28 27 26 27 24 20 18 17 20 17 18 22 18 18 18
      23 24 26 21 23 18 16 15 18 20 21 24 20 18 19 20
      19 27 28 27 19 15 15 16 20 25 25 22 18 18 20 16
      22 28 28 20 17 17 20 25 27 27 27 24 21 17 17 20
      17 21 19 15 18 23 28 28 28 28 26 20 16 16 18 21
      16 15 15 17 23 25 29 28 28 22 19 16 16 17 21 21
      16 15 15 18 23 27 27 25 20 15 16 16 16 17 18 23
      18 14 18 21 24 23 17 16 17 16 15 16 16 16 19 21
      21 14 15 18 22 16 18 21 16 16 16 15 16 18 22 24

     MODAL ANALYSIS                          CLUSTER ANALYSIS
L L L . . . . . - - - - - - - -          - - - - - - - - - - - - - - - -
    . . . . . . - - - - - - - L          . . - - - - - - - - - - - - - .
    . . . . . . - - - - - - L L          L . - - - - - - - - - - - - . L
  . . . . . . . - - - - . L L L          . - - - - - - - - - - - . L L L
. . . . . . . . - - L L L L L L          - - - - - - - - - - . . L L L L
. . . . . . . - L L L L L L L .          - - - - - - - - L L L L L L . .
. . . . . .     L L L L L L L -          - - - - - - . L L L L L L . . -
. . . . . L     L L L L . L L L          - - - - - - . L L . L L . L L L
. . - . . L L - L . . - . L L .          . - - . . L L L L . . - . L . .
L - - - - L L - . - - . L L . L          . - - - . L L L . - - . L L . L
. - - L - L L . H H H - . L L .          . - - . L L . - - - - - . L L .
L . L L - . - - H H H . L L L .          L . . L L . - - - - - . L L L .
L L L L . . - - H . L L L L . .          L L L L . - - - - . . L L L . .
L L L L . - - . . L L L L L L .          L L L L . - - - . L L L L L L .
L L L . . . L - L L L L L L L .          L L L . - . L L L L L L L L . .
. L L L . L L . L L L L L L . -          . L L L . L L . L L L L L L . -

               #    MODE 1=L  MODE 2=.  MODE 3=-  MODE 4=H      CLUSTER
             MODES  RNG CNTS  RNG CNTS  RNG CNTS  RNG CNTS  #    RNG CNTS %
QUADRANT 1     2    24-25  5  26-30 59   0- 0  0   0- 0  0 1=L  0-18 88  34
QUADRANT 2     3    15-20 33  22-22  3  24-30 28   0- 0  0 2=. 19-23 56  21
QUADRANT 3     3    14-20 34  21-25 18  26-29 12   0- 0  0 3=- 24-63112  43
QUADRANT 4     4    15-19 34  20-23 18  24-25  5  25-28  7 4=H  0- 0  0   0
```

Figure 10. MODAL and CLUSTER Analysis for Case 16

```
SAMPLE #217          MODAL-CLUSTER ANALYSIS   6-BIT IR GRAYSHADES

IMAGE 40002-139
ORBIT #2755        DEC. 18, 1979
TV LIN 341         CLOUDS: SC   CLR
TV ELE 441         BKGND: WAT

      29 29 27 24 23 24 23 24 25 18 23 27 28 29 25 17
      30 27 22 23 27 29 29 29 27 26 23 20 21 26 29 26
      30 30 21 20 26 27 23 22 28 29 25 21 23 25 29 28
      28 29 24 19 21 21 18 21 28 25 20 25 28 27 23 25
      29 28 28 27 21 18 19 20 27 24 24 29 28 28 25 24
      19 20 29 27 19 21 19 22 27 27 24 28 27 27 27 21
      17 19 22 21 18 21 23 25 26 27 26 29 29 28 27 22
      18 16 19 22 26 25 24 25 22 28 28 28 29 28 26 19
      26 25 19 26 29 26 20 19 24 28 29 27 28 28 28 19
      30 29 25 27 28 26 19 22 29 29 29 26 27 29 28 20
      27 28 28 27 23 19 17 25 29 25 25 19 25 28 29 27
      20 28 29 23 23 28 27 28 29 28 23 22 26 28 28 28
      21 25 25 23 29 29 28 28 28 26 25 28 28 28 28 28
      23 26 28 29 28 27 27 29 27 19 25 28 28 28 28 28
      21 27 29 28 29 28 28 29 22 21 26 28 28 26 28 28
      21 28 29 28 29 28 29 25 17 19 21 28 28 26 26 28

        MODAL ANALYSIS                          CLUSTER ANALYSIS
. . . L L L L L . L . - - - . L        - - - . L . L . . L L - - - . L
. . L L . . . . - - . L L - - -        - - L L - - - - - . L L L . - .
. . L L . . L L - - . L . . - -        - - L L . - L L - - . L L . - -
. . L L L L L L - . L . - - . .        - - . L L L L L - . L . - - L .
. . . . L L L L - . . - - - . .        - - - - L L L L - . . - - - . .
L L . . L L L L - - . - - - - L        L L - - L L L L - - . - - - - L
L L L L L L L L - - - - - - - .        L L L L L L L . . - . - - - - L
L L L L . L L L . - - - - - - L        L L L L . . . . L - - - - - . L
H - L H H H . L . . . . . . . L        . . L . - . L L . - - - - - - L
H H - H H H L . . . . . . . . L        - - . - - . L L - - - . - - - L
H H H H . L   - . . . L . . . .        - - - - L L L . - . . L . - - -
. H H . . H H H . . . L . . . .        L - - L L - - - - - L L . - - -
. - - . H H H H . . . . . . . .        L . . L - - - - - . . - - - - -
. H H H H H H H . L . . . . . .        L . - - - - - - - L . - - - - -
. H H H H H H H L L . . . . . .        L - - - - - - - L L . - - . - -
. H H H H H H -   L L . . . . .        L - - - - - - . L L L - - . . -
```

	# MODES	MODE 1=L RNG	CNTS	MODE 2=. RNG	CNTS	MODE 3=- RNG	CNTS	MODE 4=H RNG	CNTS	CLUSTER #	RNG	CNTS	%
QUADRANT 1	2	16-25	42	26-30	22	0- 0	0	0- 0	0	1=L	0-23	75	29
QUADRANT 2	3	17-21	8	22-25	18	26-29	38	0- 0	0	2=.	24-26	52	20
QUADRANT 3	[illegible]	19-19	4	20-23	11	25-25	6	26-30	42	3=-	27-63	129	50
QUADRANT 4	[illegible]	19-22	9	23-29	54	0- 0	0	0- 0	0	4=H	0- 0	0	0

Figure 11. MODAL and CLUSTER Analysis for Case 217

```
SAMPLE # 62              MODAL-CLUSTER ANALYSIS    6-BIT IR GRAYSHADES

IMAGE 35002-130
DMHIT #2690          DEC. 12, 1979
TV LIN 275           CLOUDS: SC
TV ELE 302           BKGND: WAT

        20 21 21 22 21 20 21 21 21 24 23 22 21 22 22 24
        21 22 21 21 21 21 21 23 23 23 22 22 24 25 25 24
        21 21 23 22 23 26 24 23 23 23 23 25 24 22 22 22
        21 22 22 22 22 23 25 23 23 23 23 24 23 23 22 22
        22 22 23 22 23 22 23 22 22 22 22 22 22 21 21 22
        23 22 22 20 21 21 21 21 21 22 22 22 21 21 21 21
        22 23 22 21 22 23 24 22 21 21 21 22 22 23 22 21
        22 22 23 21 23 24 22 21 21 20 21 21 22 22 23 22
        20 21 22 22 22 22 21 21 21 21 21 22 22 22 22 22
        20 20 20 21 21 21 21 21 21 22 21 21 21 21 21 22
        20 20 20 21 21 21 20 21 21 21 21 20 19 19 19 20
        22 22 22 22 22 22 20 20 19 20 19 20 20 20 21 21
        23 23 23 23 23 23 23 22 22 21 21 21 20 20 21 21
        23 23 23 23 23 23 23 23 23 22 21 20 20 21 21 21
        24 23 23 23 23 22 22 21 21 21 21 20 21 20 18 17
        22 22 22 22 21 21 21 21 21 20 20 19 19 19 17 15

       MODAL ANALYSIS                         CLUSTER ANALYSIS
L L L L L L L L L L L L L L L L        L L L . L L L L L . . . L . . .
L L L L L L L L L L L L L L L L        L . L L L L L . . . . . . . . .
L L L L L L L L L L L L L L L L        L L . . . . . . . . . . . . . .
L L L L L L L L L L L L L L L L        L . . . . . . . . . . . . . . .
L L L L L L L L L L L L L L L L        . . . . . . . . . . . . . L L .
L L L L L L L L L L L L L L L L        . . . L L L L L L . . . L L L L
L L L L L L L L L L L L L L L L        . . . L . . . . L L L . . . . L
L L L L L L L L L L L L L L L L        . . . L . . . L L L L L . . . .
L L L L L L L L L L L L L L L L        L L . . . . L L L L L . . . . .
L L L L L L L L L L L L L L L L        L L L L L L L L L . L L L L L .
L L L L L L L L L L L L L L L L        L L L L L L L L L L L L L L L L
L L L L L L L L L L L L L L L L        . . . . . . L L L L L L L L L L
L L L L L L L L L L L L L L L L        . . . . . . . . . L L L L L L L
L L L L L L L L L L L L L L L L        . . . . . . . . . . L L L L L L
L L L L L L L L L L L L L L L          . . . . . . . L L L L L L L L L
L L L L L L L L L L L L L L            . . . . L L L L L L L L L L L L
```

	#	MODE 1=L		MODE 2=.		MODE 3=-		MODE 4=H			CLUSTER		
	MODES	RNG	CNTS	RNG	CNTS	RNG	CNTS	RNG	CNTS	#	RNG	CNTS	%
QUADRANT 1	1	20-26	64	0- 0	0	0- 0	0	0- 0	0	1=L	0-21	122	47
QUADRANT 2	1	20-25	64	0- 0	0	0- 0	0	0- 0	0	2=.	22-63	134	52
QUADRANT 3	1	20-24	64	0- 0	0	0- 0	0	0- 0	0	3=-	0- 0	0	0
QUADRANT 4	1	18-23	61	0- 0	0	0- 0	0	0- 0	0	4=H	0- 0	0	0

Figure 12. MODAL and CLUSTER Analysis for Case 62

```
SAMPLE #209          MODAL-CLUSTER ANALYSIS   6-BIT IR GRAYSHADES

IMAGE 40002-130
ORBIT #2755          DEC. 18, 1979
TV LIN  57           CLOUDS: SC    CLL   CLM
TV ELE 337           BKGND: MIX

         34 29 28 28 30 33 32 32 34 36 37 37 37 37 37 38
         34 28 27 27 28 30 30 30 31 34 34 35 37 37 37 37
         35 30 27 27 27 28 29 28 28 31 31 34 35 35 35 36
         35 32 27 27 27 27 27 29 29 29 32 33 33 35 35 35
         36 33 28 27 26 26 27 30 28 31 33 33 33 34 36 37
         35 33 28 27 27 27 27 29 29 31 33 34 33 35 37 38
         35 32 27 27 27 28 28 27 30 32 36 36 35 35 35 36
         32 30 27 27 27 28 28 28 30 33 36 38 37 36 36 36
         30 30 28 28 28 28 28 29 29 31 32 35 35 35 35 35
         30 31 31 29 30 31 30 29 28 27 28 30 31 32 32 32
         32 34 34 33 34 35 34 28 28 27 27 28 30 32 36 34
         34 35 35 35 35 35 35 31 27 27 27 27 30 32 34 32
         35 35 35 36 36 35 34 28 27 27 27 28 29 32 34 32
         35 35 36 36 36 36 34 28 27 26 27 28 28 31 32 33
         36 35 35 36 35 35 34 29 27 27 27 27 28 29 30 32
         35 35 35 36 36 36 36 35 30 28 27 27 28 28 28 29

          MODAL ANALYSIS                          CLUSTER ANALYSIS
- L L L . - - - - - - - - - - -           - . L L . . . . - - - - - - - -
- L L L L . . . . - - - - - - -           - L L L L . . . . - - - - - - -
H . L L L L L L L . . - - - - -           - . L L L L . L L . . - - - - -
H - L L L L L L L L . . . - - -           - . L L L L L . . . . . . - - -
H - L L L L L . L . . . . - - -           - . L L L L L . L . . . . - - -
H - L L L L L L L . . - . - - -           - . L L L L L . . . . - . - - -
H - L L L L L L . . - - - - - -           - . L L L L L L . . - - - - - -
- . L L L L L L . . - - - - - -           . . L L L L L L . . - - - - - -
L L L L L L L L L . . . . . . .           . . L L L L L . . . . - - - - -
L L L L L L L L L L L . . . . .           . . . . . . . . L L L . . . . .
. . . . . . . L L L L L . . . .           . - - . - - - L L L L L . . - -
. . . . . . . L L L L L . . . .           - - - - - - - . L L L L . . - .
. . . . . . . L L L L L L . . .           - - - - - - - L L L L L . . - .
. . . . . . . L L L L L L . . .           - - - - - - - L L L L L L . . .
. . . . . . . L L L L L L L . .           - - - - - - - . L L L L L . . .
. . . . . . . . . L L L L L L L           - - - - - - - - . L L L L L L .
```

	# MODES	MODE 1=L RNG	CNTS	MODE 2=. RNG	CNTS	MODE 3=- RNG	CNTS	MODE 4=H RNG	CNTS	CLUSTER #	RNG	CNTS	%
QUADRANT 1	4	26-29	42	30-30	7	32-34	10	35-36	5	1=L	0-28	79	30
QUADRANT 2	3	28-29	5	30-33	17	34-38	42	0- 0	0	2=.	29-33	78	30
QUADRANT 3	2	28-31	21	32-36	43	0- 0	0	0- 0	0	3=-	34-63	99	38
QUADRANT 4	2	26-29	35	30-36	29	0- 0	0	0- 0	0	4=H	0- 0	0	0

Figure 13. MODAL and CLUSTER Analysis for Case 209

```
SAMPLE #301            MODAL-CLUSTER ANALYSIS   6-BIT IR GRAYSHADES

IMAGE 38002-130
ORBIT #2751          DEC. 17, 1979
TV LIN 320           CLOUDS: SC
TV ELE 422           BKGND: WAT

        30 30 33 33 33 31 32 32 33 34 34 35 35 35 35 35
        32 32 33 34 32 30 31 31 33 34 34 35 35 35 35 34
        32 33 33 34 33 31 31 33 35 34 33 34 34 34 34 34
        33 33 33 33 33 29 30 32 34 33 33 33 33 33 33 33
        33 33 32 31 31 30 28 33 33 33 31 32 32 32 32 33
        33 33 32 28 29 31 29 31 32 31 28 31 30 31 29 31
        33 32 30 27 32 29 29 32 32 29 27 30 26 27 27 32
        32 31 30 31 31 28 30 32 31 28 27 27 25 27 31 33
        30 29 29 30 28 27 31 32 31 28 28 28 29 28 32 32
        27 27 27 29 27 27 28 31 31 28 29 30 30 30 32 31
        29 29 29 30 27 27 26 27 29 30 30 29 30 31 32 31
        30 30 30 28 27 28 26 26 28 30 31 31 32 32 31 31
        30 32 32 28 26 30 27 28 28 28 30 32 33 32 30 31
        29 31 32 28 26 29 27 27 26 26 30 31 33 32 33 31
        30 31 32 29 26 29 30 29 26 25 28 31 32 32 32 31
        31 31 32 30 26 29 31 29 27 29 31 32 32 32 31 31

     MODAL ANALYSIS                          CLUSTER ANALYSIS
L L L L - L L - . . . . . . . .        . . - - - . - - - - - - - - - -
L L L L - L L - . . . . . . . .        - - - - - . . . - - - - - - - -
L L L L - L L - . . . . . . . .        - - - - - . . - - - - - - - - -
L L L L - L L - . . . . . . . .        - - - - - . . - - - - - - - - -
L L L L - L L - . . . . . . . .        - - - . . . L - - - . - - - - -
L L L L - L L - . . . . . . . .        - - - L . . . . - . L . . . . .
L L L L - L L - . . L . L L L .        - - . L - . . - - . L . L L L -
L L L L - L L - . . L L L L . .        - . . . . L . - . L L L L L . -
. L L . - L . . . L L L . L . .        . L . . L L . - . L L L . L - -
L L L L - L L . . L . . . . . .        L L L . - L L . . L . . . . - .
L L L . - L L - . . . . . . . .        . L . . L L L L . . . . . . - .
. . . L - L L - L . . . . . . .        . . . L L L L L L . . . - - . .
. . . L - . L - L L . . . . . .        . - - L L . L L L L . - - - . .
- . . L - L L - L L . . . . . .        . . - L L . L L L L . . - - - .
. . . L - L . - L L L . . . . .        . . - . L . . L L L L . - - - .
. . . . - L . - L . . . . . . .        . . - . L . . . L . . - - - . .
```

	# MODES	MODE 1=L RNG	CNTS	MODE 2=. RNG	CNTS	MODE 3=- RNG	CNTS	MODE 4=H RNG	CNTS	CLUSTER #	RNG	CNTS	%
QUADRANT 1	1	27-34	64	0- 0	0	0- 0	0	0- 0	0	1=L	0-28	59	22
QUADRANT 2	2	25-27	8	28-35	56	0- 0	0	0- 0	0	2=.	29-31	95	37
QUADRANT 3	2	26-29	40	30-32	24	0- 0	0	0- 0	0	3=-	32-63	102	39
QUADRANT 4	2	25-28	14	29-33	50	0- 0	0	0- 0	0	4=H	0- 0	0	0

Figure 14. MODAL and CLUSTER Analysis for Case 301

```
SAMPLE #199              MODAL-CLUSTER ANALYSIS   6-BIT IR GRAYSHADES

IMAGE 31002-120
ORBIT #2755          DEC. 18, 1979
TV LIN 271           CLOUDS: CS    CU
TV ELE 422           BKGND: WAT

        48 49 52 52 51 50 52 52 51 47 44 39 42 46 47 49
        45 45 50 52 49 48 49 50 51 46 47 44 43 45 48 48
        46 45 45 49 47 46 47 48 51 49 48 49 45 45 45 48
        46 47 44 47 48 48 47 47 49 49 49 50 50 47 45 47
        48 47 42 46 46 50 47 47 47 45 48 49 50 46 44 45
        47 47 43 41 45 47 47 47 46 47 49 49 49 44 41 42
        45 48 49 42 42 45 45 44 44 45 45 48 42 46 41 35
        49 45 51 48 46 47 45 45 41 39 39 46 36 41 30 25
        50 45 50 49 43 42 42 45 42 36 30 35 26 26 25 24
        49 45 50 46 40 37 42 45 37 32 27 26 25 23 23 22
        43 45 50 44 36 36 42 42 31 27 27 25 23 22 22 23
        32 35 35 35 33 36 42 34 25 24 25 24 22 23 25 23
        30 29 30 30 30 30 35 26 24 23 23 23 24 24 25 24
        25 29 29 27 27 26 27 24 23 23 23 24 24 24 24 24
        29 30 24 26 25 24 23 23 23 23 23 23 23 24 23 24
        24 29 27 25 24 21 23 22 23 23 22 23 23 24 24 24

     MODAL ANALYSIS                           CLUSTER ANALYSIS
. . - - . . - - H H - L . H H H       - - - - - - - - - - - - - - - -
. . . - . . . . H H H - - - H H       - - - - - - - - - - - - - - - -
. . . . . . . . H H H H H - - H       - - - - - - - - - - - - - - - -
. . . . . . . . H H H H H H - H       - - - - - - - - - - - - - - - -
. . L . . . . . H H H H H H - -       - - - - - - - - - - - - - - - -
. . . L . . . . H H H H H - . .       - - - - - - - - - - - - - - - -
. . . L - . . . - - - H . H .         - - - - - - - - - - - - - - - .
. . . . . . . . . - L H   .           - - - - - - - - - - - - . - . L
H - H H - - - - L L L L L L L L       - - - - - - - - - . . . L L L L
H - H H . . - - L L L L L L L L       - - - - - . - - . . . L L L L L
- - H - . . - - L L L L L L L L       - - - - . . - - . . . L L L L L
. . . . . . - . L L L L L L L L       . . . . . . - . L L L L L L L L
L L L L L L . - L L L L L L L L       . . . . . . . L L L L L L L L L
L L L L L L L   L L L L L L L L       . . . . . L . L L L L L L L L L
L L L L L       L L L L L L L L       . . . L L L L L L L L L L L L L
L L L L         L L L L L L L L       . . . L L L L L L L L L L L L L

               #    MODE 1=L  MODE 2=.  MODE 3=-  MODE 4=H       CLUSTER
             MODES  RNG CNTS  RNG CNTS  RNG CNTS  RNG CNTS   #    RNG CNTS  %
QUADRANT 1     3    41-42  4  43-51 55  52-52  5   0- 0  0  1=L   0-26  68  26
QUADRANT 2     4    39-39  3  41-42  7  43-45 13  46-51 37  2=.  27-38  41  16
QUADRANT 3     4    25-30 23  32-40 12  42-46 14  48-50  7  3=-  39-53 147  57
QUADRANT 4     1    22-42 64   0- 0  0   0- 0  0   0- 0  0  4=H   0- 0   0   0
```

Figure 15. MODAL and CLUSTER Analysis for Case 199

Cirrus. Both algorithms tend to find too many layers of cirrus. MODAL's over-analysis appears to be worse than CLUSTER's, however. Cirrus boundaries naturally are the cause for this problem, as transition zones among solid cirrus and other regions are partially filling the sensor field-of-views. Also, cirrus variations in thickness and, hence, radiative temperature contribute to this problem. While some altitude variation of cirrus is expected, the algorithms respond too strongly to field-of-view and emissivity variations. As with previous cases, these sensitivities should be tuned out of the operational algorithm.

Cumulonimbus. Both algorithms have little problem detecting the presence of cold regions adjacent to warm regions; however, both algorithms tend to be too sensitive to Cb edges. MODAL seems to find more layers at the Cb edges (Figure 16) than CLUSTER. It is interesting to note that in many Cb cases where MODAL has "undefined" pixels (see Step 5 of MODAL in Section 2.1), clouds are generally found. In addition, these areas seem to be where CLUSTER "overanalyzes."

3.3 Frequencies of Clusters and Modes

The 350 cases were reexamined to study the tendency of MODAL and CLUSTER to find too many cloud layers. For this study, we looked at clear cases that were entirely clear, and cloudy cases with only one category of cloud. We were left with 47 clear cases; 27 with a mixture of land and water, and 20 with a uniform background. We also found 168 suitable cloudy cases. The cloudy cases could be overcast or partly cloudy, as long as the background was uniform and only one cloud category was present in each case. The objective was to identify cases where the McIDAS observer, using both IR and visible imagery, found only one or two regions per case, so that only one or two clusters or modes would be the desired result of the algorithms.

Figure 17 shows the percent distributions of the numbers of clusters and modes for these cases. Cirrostratus and cumulonimbus are not shown since there were too few cases to define a distribution. CLUSTER performed well for cumulus cases since the desired one or two clusters were found 86 percent of the time. For clear cases, both MODAL and CLUSTER performed well. There were a few cases over cold land or snow where CLUSTER found two or three clusters when only one was desired. The larger array size for CLUSTER may be more sensitive to thermal gradients over clear land than the smaller array for MODAL. We will look at this in future studies to ensure that the colder land clusters are not improperly identified as clouds.

SAMPLE #349 MODAL-CLUSTER ANALYSIS 6-BIT IR GRAYSHADES

IMAGE 30072-120
ORBIT #2737 DEC. 16, 1979
TV LIN 257 CLOUDS: CS CI
TV ELE 237 BKGND: WAT

62	62	62	62	62	62	62	62	62	61	60	59	60	61	62	62
62	62	62	62	62	62	62	62	62	62	62	62	62	62	62	62
62	62	62	62	62	62	62	62	62	62	62	62	62	62	62	62
62	62	62	62	62	62	62	62	62	62	62	62	62	62	62	62
59	59	62	62	62	62	62	62	62	62	62	62	62	62	62	62
53	55	55	54	57	62	62	61	60	61	62	62	62	62	62	62
49	47	44	45	52	49	57	53	61	61	62	62	62	62	62	62
43	44	41	38	35	36	40	42	53	60	62	62	61	62	62	62
47	43	47	43	39	36	35	34	32	32	43	53	54	59	62	61
45	41	40	41	43	44	43	42	40	35	30	34	41	51	57	59
43	44	44	43	36	33	35	34	36	39	39	36	30	30	39	46
31	27	25	20	30	34	40	35	26	29	35	38	38	37	37	39
33	35	34	27	23	22	21	20	21	21	23	25	31	33	33	31
32	34	35	35	34	40	25	23	20	21	23	26	28	33	33	26
27	31	32	32	33	39	34	35	25	22	22	24	30	30	32	28
22	25	25	22	23	27	25	29	26	22	21	24	29	31	32	32

MODAL ANALYSIS

.	.	.	.	.	.	.	.	L	L	L	L	L	L	L	L
.	.	.	.	.	.	.	.	L	L	L	L	L	L	L	L
.	.	.	.	.	.	.	.	L	L	L	L	L	L	L	L
.	.	.	.	.	.	.	.	L	L	L	L	L	L	L	L
L	L	.	.	.	.	.	.	L	L	L	L	L	L	L	L
L	L	L	L	L	.	.	.	L	L	L	L	L	L	L	L
				L		L	L	L	L	L	L	L	L	L	L
									L	L	L	L	L	L	L
H	H	H	H	H	-	-	-	-	-	H	-	H	H	H	H
H	H	H	H	H	H	H	H	H	H	-	-	H	H	H	H
H	H	H	H	-	-	-	-	H	H	H	-	-	-	H	H
-	.	.	.	-	-	H	-	.	-	H	H	H	H	H	H
-	-	-	.	-	L	L	-	L	-	.	.	-	-	-	-
-	-	-	-	-	-	.	-	L	-	.	.	-	-	-	.
.	-	-	-	-	H	-	-	.	-	L	.	-	-	-	-
L	.	.	L	-	.	.	.	.	-	L	.	-	-	-	-

CLUSTER ANALYSIS

H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
H	H	-	H	H	H	H	H	H	H	H	H	H	H	H	H
-	-	-	.	.	.	-	-	H	H	H	H	H	H	H	H
H	H	H	-	-	.	.	.	.	.	-	H	H	H	H	H
-	-	-	-	-	-	-	-	-	.	.	.	-	H	H	H
-	-	-	-	.	.	.	.	.	-	-	.	.	.	.	-
.	L	L	L	.	.	-	.	L	.	.	.	.	.	.	-
.	.	.	L	L	L	L	L	L	L	L	L	.	.	.	.
.	.	.	.	.	.	L	L	L	L	L	L	L	.	.	L
L	.	.	.	.	.	.	.	L	L	L	L	.	.	.	L
L	L	L	L	L	L	L	L	L	L	L	L	.	.	.	.

	# MODES	MODE 1=L RNG CNTS	MODE 2=. RNG CNTS	MODE 3=- RNG CNTS	MODE 4=H RNG CNTS	CLUSTER #	CLUSTER RNG CNTS	%
QUADRANT 1	2	52-59 19	61-62 41	0- 0 0	0- 0 0	1=L	0-28 39	15
QUADRANT 2	1	59-62 63	0- 0 0	0- 0 0	0- 0 0	2=.	29-30 59	23
QUADRANT 3	4	21-25 8	25-28 11	30-36 26	39-49 19	3=-	39-46 28	[illegible]
QUADRANT 4	4	20-22 8	23-25 10	28-34 22	35-62 24	4=H	47-63 130	50

Figure 16. MODAL and CLUSTER Analysis for Case 349

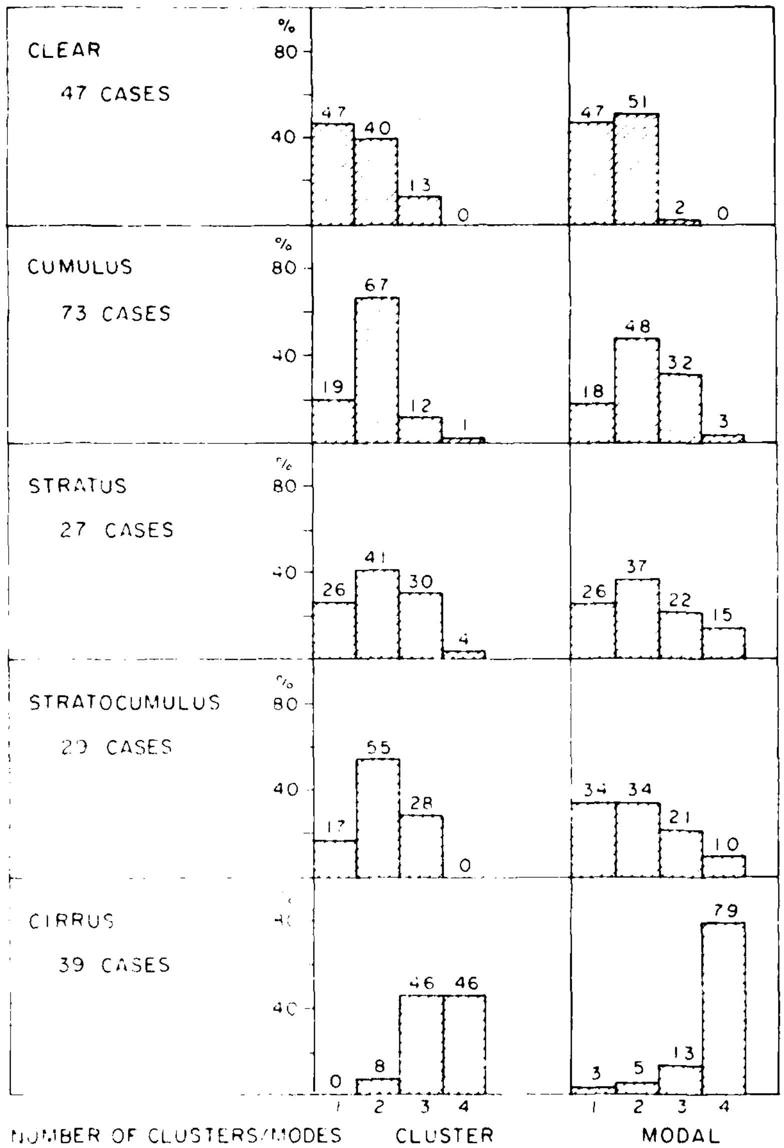

Figure 17. Percent Distribution of the Numbers of Clusters/Modes for Entirely Clear Cases and Cloudy Cases With Only One Category of Cloud Per Case.

The cloudy categories in Figure 17 confirm the examples in the previous section. Both MODAL and CLUSTER are tending to overanalyze cloud layers, finding 3 or 4 modes or clusters when only 1 or 2 are desired. Moreover, MODAL is overanalyzing more frequently than CLUSTER. The cirrus cases are the worst. (The few cases of pure cirrostratus and cumulonimbus also tended to have 3 or 4 modes or clusters.) It can be argued that cirrus may be found in multiple layers so that 3 or 4 clusters or modes would be acceptable for some cases. Nothing in our meteorological experience, however, leads us to believe that this should happen 92 percent of the time as Figure 17 shows when the percentages for 3 and 4 clusters/modes are summed.

Two further comments related to the excessive number of modes found by MODAL should be made. First, the most recent technical report on the 3DNEPH[2] states that a mode is defined for a single grayshade that contains 6 or more samples, or a group of adjacent grayshades containing 12 or more samples. This is no longer the case in MODAL, since a single grayshade that contains 3 or more samples can presently define a mode. These "small" modes contribute heavily to MODAL's tendency to find more modes than observers can find in the IR or visible imagery. The second comment is that not all the modes in MODAL are designated as separate cloud layers by the 3DNEPH. There are somewhat arbitrary rules elsewhere in the 3DNEPH code for combining the modes into no more than two cloudy layers. Although we did not duplicate these rules in this study, we suspect that the overanalysis of modes will still be detrimental to the final cloud layers in the 3DNEPH, at least when cirrus is present, and probably for other cloud categories as well.

As anticipated, both algorithms performed extremely well (over 90 percent accuracy) when analyzing samples where only one mode or cluster was desired. It should be noted, however, that the majority of cases containing only one homogeneous region were clear land, water, or snow and uniform stratus, imagery types that present only minor problems to the algorithms.

3.4 Preliminary Cloud Cover Evaluation

While cases were being identified and saved on the McIDAS, the image analysts made subjective estimates of the fraction of cloud categories over the 16 x 16 array of IR values. The observer could look at both visible and IR images so that the estimates of cloud cover for low clouds were generally trustworthy, and were assumed accurate to ±10 percent. As in the previous section, "simple" cloud cases with only one cloud category appearing in each case were studied. An observer reviewed each case for both MODAL and CLUSTER, identified the cloudy modes and clusters, and calculated the total cloud cover for each 16 x 16

array based on the numbers of samples in the cloudy modes and clusters. The observer was performing the role of the 3DNEPH surface temperature field in separating the clear and cloudy modes or clusters. (This was a time-consuming technique that we will endeavor to improve for future cloud analysis studies on the McIDAS.) Results are given in Tables 4 and 5.

Table 4. Cloud Cover Within 10 Percent of Observed

	CLUSTER	MODAL	Total Cases
Cu	38%	25%	52
St	61%	70%	23
Sc	80%	60%	25
Ci	50%	38%	34
All Four Categories	53%	43%	134

Table 5. Cloud Cover Closest to Observed

	CLUSTER	MODAL	Ties	Total Cases
Cu	46%	42%	12%	52
St	30%	13%	57%	23
Sc	44%	28%	28%	25
Ci	38%	47%	15%	34
All Four Categories	41%	36%	23%	134

Table 4 shows the percentages of cases that had cloud cover within 10 percent of the observed. For the total of the four categories of clouds, CLUSTER performed better than MODAL (53 percent compared to 43 percent) but there is obviously room for improvement for both algorithms. The cloud cover estimates were weakest for cumulus and cirrus categories, which is expected since these categories are most likely to have subpixel cloud elements and highly variable changes in cloud emissivities from one pixel to the next. The categories with

larger cloud elements, St and Sc, had more accurate cloud cover estimates for both algorithms.

Table 5 shows the percentages of cloud cover estimates that were closest to the observed values on a case-by-case basis. CLUSTER had cloud cover estimates closest to observed for 3 out of 4 categories, and for the sum of all categories; however, the differences between MODAL and CLUSTER are not great in this comparison.

The average cloud covers for observed, MODAL, and CLUSTER estimates were calculated for each category to see if the algorithms were finding more or less clouds than the observed. Very little difference was found for Cu, St, and Sc, but MODAL and CLUSTER both found about 5 percent more Ci than the image observers. The image observer estimates of Ci coverage often seemed low compared to hand-drawn contour analyses of the 16 x 16 arrays of IR data. For this cloud category, moreover, the visible data was not very helpful for estimates of cloud cover from the image displays.

The subjective estimates of percent cloud cover were almost indispensable for evaluating the performance of CLUSTER and MODAL, and have convinced us that interactive computer procedures should be established for improved cloud cover verification in future studies.

4. CONCLUSIONS

We have evaluated the 3DNEPH MODAL algorithm, along with an alternative CLUSTER algorithm, and have found that CLUSTER performs better. The CLUSTER algorithm finds clear/cloud boundaries, numbers of cloud layers, and fractions of cloud cover that are closer to those estimated by observers evaluating the IR and visible images. The MODAL algorithm finds more cloud layers than are observed, and tends to overanalyze regions of transition from one layer to another. The CLUSTER algorithm is designed to assign all points to a layer in an optimal manner. The MODAL algorithm frequently (27 percent of the time) terminates its histogram analysis with unassigned points. These points are later assigned to warmer modes, which will tend to overestimate the altitudes of clouds in those modes (except cirriform categories), since the 3DNEPH uses the coldest grayshade in a mode to represent the entire mode. CLUSTER uses a larger array of satellite data, and appears to benefit from the extra information by improved detection of low clouds such as cumulus. CLUSTER, moreover, produces all the information necessary for cloud cover estimates at the same mesh size as the 3DNEPH. On the McIDAS, CLUSTER takes very nearly the same computer time as MODAL, so that its computational requirements are reasonable.

Despite the overall advantages of CLUSTER, there is considerable room for improvement, and algorithm development leading to accurate cloud analysis should continue. In particular, CLUSTER finds too many layers of cirrus clouds, and the fractional coverage of both cumulus and cirrus clouds usually differs from the apparent coverage on the satellite images. When thermal gradients are found in clear land or snow, it can also find two or three clusters when only one is desired. The MODAL analyses were slightly better in these areas.

Unlike MODAL, the CLUSTER algorithm can be tuned in a number of places to reduce sensitivity, and give results closer to those that actually exist. For instance, it might be possible to improve cirrus layering by increasing the interval sizes in the cold temperatures. Surface regions can be simplified; that is, analyzed into fewer clusters, by increasing the minimum size of a cluster. These are but two examples of how CLUSTER is open to tuning by making very simple alterations to the algorithm. There are other places in the algorithm code where simple modifications can be made to better model specific meteorological conditions that occur commonly on a global basis.

The AFGWC has recognized the limitations of MODAL, and the complexity in computer code, so that a substantially revised version has been written for the planned upgrade of the 3DNEPH known as the Real-Time Nephanalysis (RTNEPH).

With the continued cooperation of AFGWC, and drawing on our experience with MODAL and CLUSTER, we plan to evaluate the RTNEPH satellite analysis algorithm. We also plan to use the capabilities of the McIDAS system for improving estimates of "cloud truth" for the evaluation and refinement of the cloud analysis algorithms. Finally, we shall propose the use of a modified CLUSTER algorithm, developed at AFGL, in replacement of, or in tandem with, the RTNEPH/3DNEPH image analysis algorithms.

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